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Personal Sampling of Particles in Adults: Relation among Personal, Indoor, and Outdoor Air Concentrations

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To investigate the validity of outdoor particulate matter with a 50% cutoff diameter of 10-μm (PM_{10}) concentrations as a measure of exposure in time series studies, the association between personal and outdoor concentrations, within subjects, over time was investigated. Repeated measurements of personal, indoor, and outdoor PM_{10} were conducted among 37 nonsmoking, 50- to 70-year-old adults, living in Amsterdam, Netherlands, 1994. Regression analyses were conducted for each subject separately, and the distribution of the individual regression and correlation coefficients was investigated. Furthermore, the extent to which differences among personal, indoor, and outdoor concentrations could be explained was studied. The median Pearson's R between personal and outdoor concentrations was 0.50. Excluding days with exposure to environmental tobacco smoke (ETS) improved the correlation to a median R of 0.71. The estimated cross-sectional correlations were lower, 0.34 and 0.50, respectively. Outdoor concentrations (mean, 42 $\mu g/m^3$) exceeded indoor concentrations (mean, 35 $\mu g/m^3$) but underestimated personal exposures (mean, 62 $\mu g/m^3$). The major part of the difference between personal and outdoor concentrations could be attributed to exposure to ETS, living along a busy road, and time spent in a vehicle. The results show a reasonably high correlation between personal and outdoor PM_{10} within individuals, providing support for the use of ambient PM_{10} concentrations as a measure of exposure in epidemiologic studies linking the day-to-day variation in particulate matter air pollution to the day-to-day variation in health endpoints such as mortality, hospital admissions, respiratory symptoms, and lung function. *Am J Epidemiol* 1998;147:537–47.

air pollutants, environmental; air pollution; tobacco smoke pollution

Recent epidemiologic studies have documented associations between particulate matter air pollution and several acute health effects, including mortality, hospital admissions, respiratory symptoms, and lung function (1–7). These studies are mostly time series studies, relating day-to-day variation in air pollution to day-to-day variation in health endpoints. In these studies, exposure assessment is based on fixed site measurements in ambient air. It has been suggested that particulate matter concentrations from fixed sites correlate poorly with personal exposures (8). Sexton et al. (9) and Spengler et al. (10) found values of 0.06 and 0.07, respectively, for the correlation between personal and ambient respirable suspended particulates. More recently, in the particle total exposure assessment methodology (PTEAM) study, the correlation between 24-hour averaged personal and ambient particulate matter with a 50 percent cutoff diameter of 10 μm (PM_{10}) was 0.48 (11). If the variation in outdoor levels of particulate matter is not tightly linked to variation in personal exposures, the use of outdoor concentrations as a surrogate for personal exposures would tend to misclassify personal exposures, and exposure-response relations could be attenuated (12). However, in most personal exposure studies, the correlation between personal and outdoor concentrations is calculated cross-sectionally. Personal exposure data are collected from a group of subjects by measuring different subsets of subjects on different days (equaling different ambient concentrations) and measuring each subject a limited number of times. Next, one correlation coefficient between personal and ambient concentrations is calculated, using all measurements from all subjects and days. This correlation is influenced by the variation in personal exposure among subjects. Since time series studies relate day-to-day variations in outdoor concentrations to day-to-day variations of health endpoints, the correlation between personal and ambient concentrations within persons,

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Abbreviations: ETS, environmental tobacco smoke; HI, Harvard impactor; $PM_{2.5}$, particulate matter with a 50 percent cutoff diameter of 2.5 μm; PM_{10}, particulate matter with a 50 percent cutoff diameter of 10 μm; PS, personal sampler; PTEAM, particle total exposure assessment methodology; SA, Sierra Anderson; SD, standard deviation; THEES, total human environmental exposure study.

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over time, is more relevant than the variation among persons. This correlation may be better because some aspects that can cause variation among subjects, such as smoking habits, are less variable in time within subjects and therefore mainly cause variation among subjects. At present, only limited information is available about the within-subject correlation between personal and outdoor PM_{10} concentrations (11, 13).

To investigate the validity of outdoor concentrations as a measure of exposure to PM_{10} in time series studies, information about the correlation between personal and outdoor measurements within subjects is necessary. We therefore conducted a personal exposure study in which repeated measurements of personal and outdoor PM_{10} were conducted, to allow calculation of the correlation within subjects, over time. In addition, repeated measurements of indoor PM_{10} were conducted to provide information about the personal-indoor and indoor-outdoor correlations as well. This paper describes the relation among personal, indoor, and outdoor PM_{10} concentrations in a group of 50- to 70-year-old Dutch adults.

MATERIALS AND METHODS

Study design

The personal exposure study was conducted within the framework of a panel study on acute effects of air pollution on respiratory health (14). This study was partly conducted in Amsterdam, the capital of the Netherlands, which has about 720,000 inhabitants. The major sources of air quality are local traffic and long distance transport. A number of Amsterdam subjects, who had agreed to participate in the panel study, were invited to participate in the personal exposure study. Interested nonsmoking subjects with no smokers in their households and no occupational exposure to dust received a detailed written description of the study and were then asked for final consent after approximately 1 week. Of 195 adults approached, 51 (26 percent) both met the selection criteria and agreed to participate. After the first measurement, subjects were explicitly asked whether they were sure they were able to wear the monitor another 7 times, after which 12 subjects decided to drop out. A total of 37 of the 39 remaining subjects successfully completed the study.

Measurements took place in two periods: from January 17 to March 31, 1994, involving 13 adults, and from October 17 to December 23, 1994, involving another 24 adults. Averaged 24-hour measurements of personal and indoor PM_{10} were conducted simultaneously, on weekdays only. One to 12 subjects were monitored on the same day and, for each subject, measurements were spaced approximately 1 week apart. Samplers were distributed and collected at the homes of the participants between 9:00 a.m. and 6:00 p.m. Seven to eight personal measurements per subject were planned. In the first period, indoor measurements were scheduled on only about 5 days of personal sampling because of limited indoor sampling equipment availability. In the second period, indoor measurements were conducted on all days of personal sampling. Outdoor concentrations of PM_{10} were obtained from a fixed monitoring site (see below).

Information on general characteristics such as housing conditions was assessed by questionnaire. In addition, participants were asked to fill out a more detailed questionnaire including questions on exposure to environmental tobacco smoke (ETS), time spent in several microenvironments, cleaning and cooking activities, and so on, after each individual day of personal measurements. Exposure to ETS was assessed by means of the following questions:

1. Has anybody smoked in your living room during the measurements? (*yes/no*)
   A. If yes, how much? ____ cigarettes/cigars/pipes
2. Have you been in a room, other than your own living room, where people smoked? (*yes/no*)
   A. If yes, how long did you stay there? ____ hours

Sampling methods

Personal measurements were conducted using a personal impactor described by Buckley et al. (13), using 25-mm-diameter 3-μm-pore-size Teflon filters (Gelman Sciences, Ann Arbor, Michigan) and a flow-controlled battery-operated pump (model Gil-Air 5; Gilian Instruments Corp., West Caldwell, New Jersey) at a flow rate of 4 liters/minute. Details about the sampling method and quality issues are described elsewhere (15).

Measurements of PM_{10} indoors were made with a Harvard impactor (HI) (A. D. E., Inc., Naples, Maine) operating at 10 liters/minute (16, 17), using a flow-controlled pump (model SP-280E; A. D. E., Inc.), using Anderson 37-mm-diameter 2-μm-pore-size Teflon filters (Gelman Sciences). Indoor samples were taken in the living room at a height of 1.5 m.

Outdoor PM_{10} concentrations were obtained from a fixed monitoring site operated for the panel study mentioned earlier (14). The site was located in a park in the city center, about 150 m away from the nearest busy road and away from local particle sources, such as construction work or industrial sources. At this site, measurements were conducted at 1.5-m height on a

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continuous, daily basis (from 3 p.m. to 3 p.m.), using an inlet similar to the Sierra Anderson (SA) 241 dichotomous sampler inlet (18) at a flow rate of 16.7 liters/minute. Simultaneous operation of the personal sampler (PS) with the outdoor sampler (SA) and the indoor sampler (HI) at the outdoor monitoring site did not show significant differences in outdoor concentrations obtained with the different methods. The estimated regression equations were PS = 4.6 + 0.89 × SA (R = 0.95) and PS = 0.1 + 1.09 × HI (R = 0.91) (15). The personal impactor was oriented in the same way as when it was worn during personal sampling.

For logistic reasons, it was not possible to start the personal and indoor measurements at the same time as the outdoor measurements. The average overlap between the measuring periods of personal/indoor and outdoor samples was 21 hours. For 95 percent of the measurements, the overlap was larger than 18.9 hours.

For all three types of measurements (personal, indoor, and outdoor), flows were measured at the beginning and end of each 24-hour sampling period with calibrated rotameters, and elapsed time indicators were used to calculate the sampled volumes.

Filters were weighed using a Sartorius model 1712 (Sartorius AG, Goettingen, Germany) (first period) or Mettler model AT261 (Mettler-Toledo, Greifensee, Switzerland) (second period) analytical balance with 10-μg reading, after equilibrating at about 20°C and 44 percent relative humidity for 24 hours, using desiccators. All personal filters were weighed in duplicate (15). Mean field blank weight changes were 26.1 μg (n = 27; standard deviation (SD), 20.8 μg) for the personal filters, 0.4 μg (n = 14; SD, 31.7 μg) for the indoor filters, and 58.7 μg (n = 30; SD, 77.5 μg) for the outdoor filters. These mean values were subtracted from the respective sample weights. Detection limits, defined as 3 times the standard deviation of field blanks divided by the sampled volume, were 10.8 $\mu g/m^3$, 6.6 $\mu g/m^3$, and 9.7 $\mu g/m^3$ for the personal, indoor, and outdoor measurements, respectively.

Data analysis

Correlation among personal, indoor, and outdoor PM_{10} concentrations. The correlation among personal, indoor, and outdoor PM_{10} concentrations was assessed by means of individual regression analysis, using the Statistical Analysis System (SAS Institute, Inc., Cary, North Carolina) PROC REG and PROC CORR procedures. The following models were used:

$$\text{Model 1.}\quad PM_{10_{personal,it}} = \alpha_{i1} + \beta_{i1} \times PM_{10_{outdoors,t}}$$

$$\text{Model 2.}\quad PM_{10_{personal,it}} = \alpha_{i2} + \beta_{i2} \times PM_{10_{indoors,it}}$$

$$\text{Model 3.}\quad PM_{10_{indoors,it}} = \alpha_{i3} + \beta_{i3} \times PM_{10_{outdoors,t}}$$

where i = subject i, t = day t, and 1, 2, 3 = model 1, 2, 3, respectively.

The distribution of the individual regression results was investigated. Medians are presented because most correlation and regression coefficients were not normally distributed (Shapiro-Wilk statistic, $p < 0.05$). Although all subjects were nonsmokers not living with smokers, participants could still be exposed to ETS elsewhere or at home in the case of a smoking visitor. To investigate the influence of occasional exposure to ETS on the relation among personal, indoor, and outdoor PM_{10}, the same regression analyses were conducted after excluding days with exposure to ETS. Subjects with less than four remaining observations were excluded.

For comparison purposes, we calculated what the correlation would have been, if it had been calculated cross-sectionally. In this analysis, we randomly selected one measurement per subject and next calculated the cross-sectional correlation between personal and outdoor concentrations. This procedure was repeated 1,000 times, and the median of those 1,000 correlation coefficients was calculated to get a more reliable estimate of the cross-sectional correlation.

Difference between personal and outdoor and between indoor and outdoor PM_{10} concentrations. The questionnaire data were used to examine to what extent differences between personal and outdoor and between indoor and outdoor concentrations could be explained by certain characteristics or activities, such as exposure to ETS. The difference between personal and outdoor concentrations or the difference between indoor and outdoor concentrations was used as the dependent variable in a regression analysis. The SAS PROC MIXED procedure was used to adjust regression results for correlations among repeated measurements. A random intercept model was used. In the analysis of the difference between indoor and outdoor concentrations, cooking was considered separately for homes with and without a kitchen in open connection with the living room (a so-called "open" kitchen). Different questions on cleaning activities (dusting, vacuum cleaning, sweeping, and cleaning a pet's cage) were combined into one variable "cleaning activities."

RESULTS

Population

A total of 37 adults, 18 males and 19 females, successfully completed the study. The average age was 62 (range, 51–70) years. Ten subjects (27 percent) were still employed, of whom three were teachers, two had office jobs, one was a house painter, three worked at home, and one (saleswoman) worked only 1 day per

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week. On the days of personal measurements, subjects spent on average 1.3 hours outdoors and 20.5 hours at home. One married couple participated in the study; therefore, indoor measurements were conducted in 36 houses.

All subjects lived in the inner city, within a radius of 5 km and at most 4 km from the outdoor monitoring site. Seven (19 percent) subjects lived along a busy road, defined as living on a street that was part of the Amsterdam main road network. The average number of cars passing through these seven streets was 13,500 per day (range, 7,125–17,093 cars); for trucks, the average was 670 per day (range, 307–1,086 trucks). The mean ambient temperature during the sampling period was 6°C.

Particle concentrations

From each adult, 5–8 personal concentrations and 4–9 indoor concentrations were obtained. The distributions of the individual averages of personal, indoor, and outdoor PM_{10} are presented in table 1. Outdoor concentrations exceeded indoor concentrations but considerably underestimated personal exposures. This will be discussed in more detail later.

Correlation among personal, indoor, and outdoor PM_{10} concentrations

Results from the individual regression analyses with all observations are presented in table 2 and figure 1. The median Pearson's R was 0.50 for model 1 (personal-outdoor), 0.72 for model 2 (personal-indoor), and 0.73 for model 3 (indoor-outdoor). After excluding days with exposure to ETS (table 3; figure 2), we found that the median correlation coefficients increased and that the median intercepts decreased. For models 1 and 2, only 23 of the 37 subjects were included in table 3, because the other 14 subjects did not have at least 4 days of measurements without exposure to ETS. For model 3, only the days with exposure to ETS inside the subject's own home were excluded, after which 32 homes had at least four remaining observations. For models 1 and 2, 16 of the 23 subjects included in table 3 were not exposed to ETS on any of the days of measurements, so only seven subjects had different regression results in table 3 when compared with those in table 2. For those seven subjects, after excluding the days with exposure to ETS, we found that the median Pearson's R increased from 0.50 to 0.81 for model 1 and from 0.69 to 0.78 for model 2. For model 3, only three homes had different regression results. All three homes had higher Pearson's Rs after excluding the days with exposure to ETS.

The average range per subject in outdoor concentrations (maximum minus minimum) on days of personal measurements was 48.4 $\mu g/m^3$ (SD, 11.4; range, 24–64 $\mu g/m^3$). Excluding the five subjects with the smallest range (i.e., <35 $\mu g/m^3$) did not substantially change the medians or ranges of the correlation and regression coefficients. For example, the median correlation between personal and outdoor concentrations after the exclusion was 0.51 compared with 0.50 for all subjects.

Janssen et al. (15) reported that these adults spent significantly less time outdoors and more time at home on days of personal sampling compared with other weekdays. The differences ranged from −2.3 to +0.4 hours (mean, −0.5 hours) for the time spent outdoors and from −1.6 to +3.9 hours (mean, +0.9 hours) for the time spent at home. To investigate whether this change in behavior had any influence on the relation between personal and outdoor/indoor PM_{10}, the mean differences were used to divide the subjects into two groups, and the distributions of the regression results per group were calculated. No considerable differences between the two groups were found. For example, the median Pearson's R between personal and outdoor concentrations was 0.47 for subjects who

TABLE 1. Distribution of individual averages of personal, indoor, and outdoor PM_{10}* concentrations from 50- to 70-year-old adults, Amsterdam, Netherlands, 1994

	No.	Total no. of observations	PM_{10} concentrations ($\mu g/m^3$)		
			Median	Mean	Range
Personal	37	262	56.4	61.7 (18.3)†	38.0 to 112.6
Outdoor	37	285	41.5	41.5 (4.3)	31.9 to 50.2
Indoor	36	247	34.4	35.0 (9.4)	18.6 to 65.3
Difference personal – outdoor	37	262	15.9	20.4 (17.9)	−6.4 to 68.8
Difference personal – indoor	37	231	22.4	26.9 (20.7)	−1.0 to 99.9
Difference indoor – outdoor	36	247	−10.8	−7.1 (9.3)	−20.3 to 15.2

* PM_{10}, particulate matter with a 50% cutoff diameter of 10 μm.
† Numbers in parentheses, standard deviation.

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TABLE 2. Distribution of individual regression results of personal, indoor, and outdoor PM_{10}* concentrations from 50- to 70-year-old adults, Amsterdam, Netherlands, 1994†

	Intercept (μg/m³)		Slope		Pearson's *R*	
	Median	Range	Median	Range	Median	Range
Model 1, $PM_{10_{personal}} = PM_{10_{outdoors}}$ ‡	32.7	−22.6 to 95	0.53	−0.40 to 2.08	0.50	−0.41 to 0.92
Model 2, $PM_{10_{personal}} = PM_{10_{indoors}}$ §	30.4	−138.6 to 64.7	0.90	−0.16 to 6.12	0.72	−0.10 to 0.98
Model 3, $PM_{10_{indoors}} = PM_{10_{outdoors}}$ ¶	11.5	−63.6 to 55.4	0.47	−0.10 to 2.62	0.73	−0.88 to 0.95

* PM_{10}, particulate matter with a 50% cutoff diameter of 10 μm.
† All median intercepts and regression and correlation coefficients are significant (signed rank test: $p < 0.01$).
‡ $n = 37$.
§ $n = 37$.
¶ $n = 36$.

spent >0.5 hours less time outdoors on the days of personal measurements compared with other weekdays and 0.51 for subjects with smaller differences between the time spent outdoors on days of personal measurements and other weekdays.

The median value of 1,000 cross-sectional Pearson's correlation coefficients was 0.34 (range, −0.09 to 0.67) when selecting from all observations and 0.50 (range, −0.07 to 0.83) when only the days with no exposure to ETS were selected.

Difference between personal and outdoor and between indoor and outdoor PM_{10} concentrations

In table 1 we showed that personal exposures exceeded indoor and outdoor concentrations. The mean difference between personal and outdoor concentrations was 20 $\mu g/m^3$. Indoor concentrations were on average 7 $\mu g/m^3$ lower than the corresponding outdoor concentrations, ruling out the concentrations indoor as a possible explanation for the excess personal exposures. Furthermore, the higher personal exposures cannot be explained by the use of different samplers for personal and outdoor measurements, because outdoor concentrations measured with the personal impactor did not significantly differ from the concentrations measured with the outdoor sampler (15).

Results of the analyses of the relation between the difference between personal and outdoor concentrations and several personal characteristics and activities are presented in table 4. Exposure to ETS (both at home and elsewhere), living along a busy road, and time spent in a vehicle significantly contributed to the difference between personal and ambient concentrations. Cleaning activities, cooking, time spent outdoors, sex, and ventilation did not have a significant effect. The intercept of the model is 4 $\mu g/m^3$ and does not significantly deviate from zero.

Results of the regression analyses of the difference between indoor and outdoor concentrations are presented in table 5. Smoking in the living room and cooking in a kitchen that was in open connection with the living room significantly contributed to the difference between indoor and outdoor concentrations. In contrast to what we found for personal exposures, indoor concentrations were not higher in the living room of subjects who lived along a busy road when compared with concentrations in the other living rooms.

DISCUSSION

Correlation among personal, indoor, and outdoor PM_{10} concentrations

In this study we found a reasonably high correlation between personal and outdoor PM_{10} concentrations, within subjects, over time, despite a relatively small range in outdoor concentrations. For non-ETS-exposed subjects, daily variations in ambient PM_{10} concentrations accounted for about 50 percent of the variation in personal exposures. The correlation between personal and indoor and between indoor and outdoor concentrations was even better. Correlations within subjects over time were higher than the cross-sectional correlation.

Some recent studies have also shown higher within-subject correlations than cross-sectional correlations (11, 19). In a similar study among 45 children aged 10–12 years, we found a median Pearson's *R* between personal and outdoor PM_{10} concentrations of 0.63 compared with a cross-sectional correlation of 0.28 (19). In the PTEAM pilot study, repeated measurements of PM_{10} were conducted in nine households (two persons in each household). Cross-sectionally, personal exposures were uncorrelated with outdoor concentrations but, for the 10 subjects (five homes) with 6–8 individual measurements, individual correlations ranged from −0.17 to 0.79, with a median value of 0.26 (11). In the total human environmental exposure study (THEES), Buckley et al. (13) calculated the correlation within subjects, using 9–14 per-

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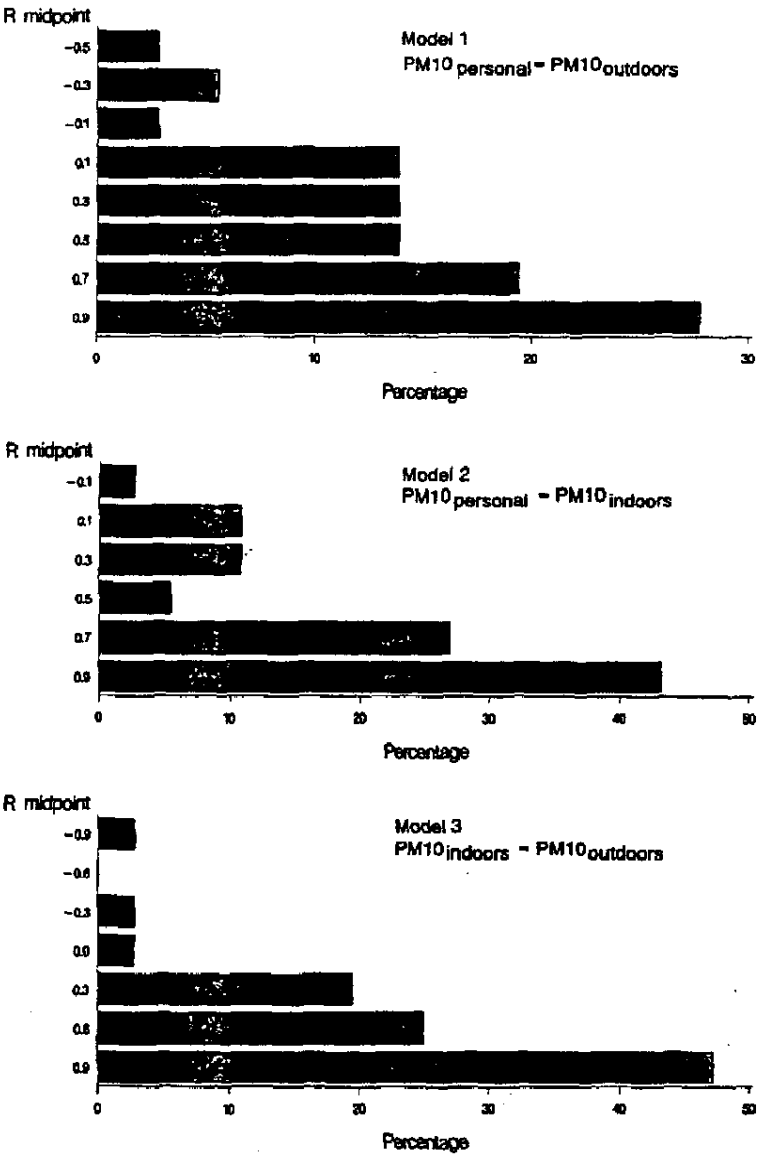

FIGURE 1. *Distribution of individual Pearson's correlation coefficients from 50- to 70-year-old adults, Amsterdam, Netherlands, 1994, with n = 37 for models 1 and 2 and n = 36 for model 3. PM_{10}, particulate matter with a 50% cutoff diameter of 10 μm.*

sonal PM_{10} measurements from 13 nonsmoking adults. Individual coefficients of the correlation between personal and ambient concentrations ranged from 0.14 to 0.90 with a median value of 0.53. Wallace (11) presented both the cross-sectional and the within-subject correlations using data from 14 subjects in the THEES study. The cross-sectional correlation between personal and outdoor concentrations was 0.52 (n = 181), whereas the median of the individual correlations was 0.68 (range, 0.14–0.91). Lioy et al. (20) reported the indoor-outdoor correlations of eight homes in the THEES study. The cross-sectional correlation (n = 101) was 0.67 compared with a median individual correlation coefficient of 0.88 (range, 0.60–0.98) (11).

After excluding the days with exposure to ETS, we found that the correlation coefficients increased. In the similar study on childhood exposure to PM_{10}, excluding the days that children with nonsmoking parents were exposed to ETS increased the correlation from a

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TABLE 3. Distribution of individual regression results of personal, indoor, and outdoor PM_{10}* concentrations from 50- to 70-year-old adults, after excluding days with exposure to environmental tobacco smoke, Amsterdam, Netherlands, 1994†

	Intercept ($\mu g/m^3$)		Slope		Pearson's R	
	Median	Range	Median	Range	Median	Range
Model 1. $PM_{10_{personal}} = PM_{10_{outdoors}}$‡	27.2	−22.6 to 82.5	0.55	−0.37 to 2.08	0.71	−0.41 to 0.94
Model 2. $PM_{10_{personal}} = PM_{10_{indoors}}$§	13.1	−16.3 to 62.1	1.00	−0.16 to 2.24	0.86	−0.10 to 0.98
Model 3. $PM_{10_{indoors}} = PM_{10_{outdoors}}$¶	11.5	−63.6 to 35.2	0.47	−0.04 to 2.62	0.75	−0.11 to 0.92

* PM_{10}, particulate matter with a 50% cutoff diameter of 10 μm.
† All median intercepts and regression and correlation coefficients are significant (signed rank test; $p < 0.01$).
‡ $n = 23$.
§ $n = 23$.
¶ $n = 32$.

median R of 0.63 to a median R of 0.73. In the THEES study (13), using activity data improved the personal estimates for all individuals, to correlation coefficients ranging from 0.58 to 0.999 with a median value of 0.93. Exposure to ETS was one of the activity variables that contributed to the improvement of the individual correlations, together with house-cleaning activities, cooking, and the use of unvented kerosene space heaters. Correlations after accounting for exposure to ETS alone were not described.

The median slope was about 0.5 for model 1 (personal-outdoor) and model 3 (indoor-outdoor) and close to one for model 2 (personal-indoor). These values are comparable with those found in the THEES and PTEAM study (11).

Individual correlation coefficients ranged from moderately negative to strongly positive values. Because of the limited number of observations per subject used to calculate the individual correlation coefficients, however, precision of individual estimates is low. Most value should therefore be put on the population median instead of individual values.

It has been argued that the low correlation between personal and outdoor exposure to particles makes associations between day-to-day variations in outdoor air pollution and health effects implausible. The significant correlation between outdoor and personal exposure found in this study documents, however, that short-term increases in outdoor air pollution are reflected in increased personal exposures. This finding provides support for using fixed site measurements as a measure of exposure to PM_{10} in time series studies linking the day-to-day variation in PM_{10} to the day-to-day variation in health endpoints.

Difference between personal and outdoor and between indoor and outdoor PM_{10} concentrations

Personal exposures considerably exceeded outdoor and indoor concentrations. The major part of the difference between personal and outdoor concentrations, however, could be attributed to exposure to ETS, living along a busy road, and the time spent in a vehicle. Indoor concentrations in the living room were lower than outdoor concentrations and were increased in the case of smoking and cooking in a kitchen in open connection to the living room.

An important part of the difference between personal and outdoor concentrations was attributed to exposure to ETS. Although all participants were nonsmokers with no smokers in their households, 21 subjects reported exposure to ETS on at least one of the days of personal measurements. The majority of the exposure to ETS occurred outside their own home environment; only seven subjects reported exposure to ETS in their own living room. The estimated contribution of one cigarette to the 24-hour average personal and indoor PM_{10} concentration was 2.3 $\mu g/m^3$, which is slightly higher than the range of 1–2 $\mu g/m^3$ that was recently suggested for particulate matter with a 50 percent cutoff diameter of 2.5 μm ($PM_{2.5}$) by Wallace (11).

Subjects who lived along a busy road had higher personal exposures than did subjects who did not live along a busy road. The estimated difference, adjusted for other factors such as exposure to ETS, was 23 $\mu g/m^3$. Indoor concentrations, however, were not higher in homes along busy streets. One possible explanation for this inconsistency might be that subjects who live along busy roads are exposed to higher PM_{10} concentrations when they go outdoors. Janssen et al. (21) found significantly higher daytime PM_{10} concentrations on the pavement of two busy roads compared with simultaneously measured background concentrations. The mean differences, however, were small: 7 $\mu g/m^3$ for the road in a town (traffic intensity, 8,900 vehicles per 24 hours) and 13 $\mu g/m^3$ for the road in a medium-sized city (traffic intensity, 15,000 vehicles per 24 hours). Bevan et al. (22) measured exposure to respirable suspended particulates while commuting by bicycle

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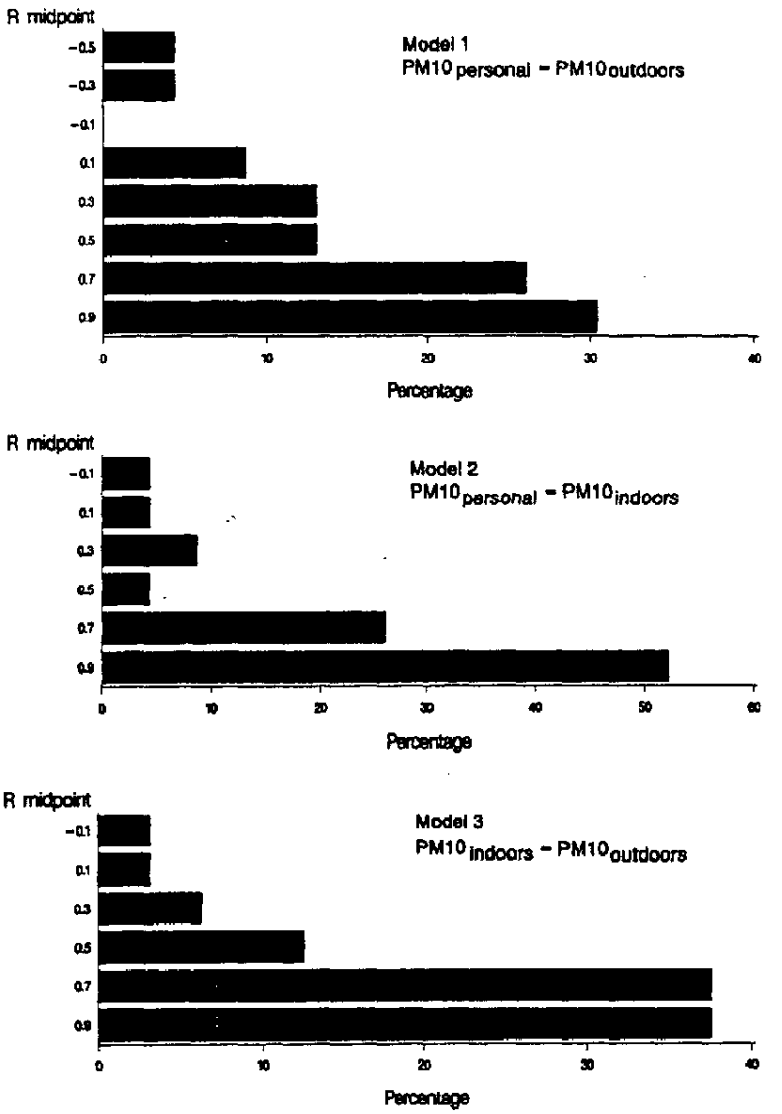

FIGURE 2. Distribution of individual Pearson's correlation coefficients from 50- to 70-year-old adults, Amsterdam, Netherlands, 1994, after excluding days with exposure to environmental tobacco smoke, with $n = 23$ for models 1 and 2 and $n = 32$ for model 3. PM_{10}, particulate matter with a 50% cutoff diameter of 10 μm.

during peak traffic hours. The mean concentration of respirable suspended particulates when cycling through a typical "urban" environment was 139 $\mu g/m^3$ compared with 120 $\mu g/m^3$ when cycling through a "suburban" area. Another aspect might be that we placed the equipment in the main living area, not necessarily being the road side of the house. Fischer et al. (23) and Oldenweening et al. (24) measured indoor and outdoor 24-hour-averaged PM_{10} and $PM_{2.5}$ concentrations in 30 houses in Amsterdam. Only the homes with the living room on the road side were selected. The mean indoor PM_{10} concentrations along busy roads were about 9 $\mu g/m^3$ higher than the mean concentration in the houses that were situated on more quiet streets. Though these studies confirm the plausibility of higher particle concentrations near busy roads, our estimated difference of 23 $\mu g/m^3$ seems rather large. Furthermore, the inconsistency of significantly higher personal exposures for subjects living along busy roads but no difference in indoor concentrations cannot readily be explained. Possibly

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TABLE 4. Multiple regression analysis of the relation between the difference between personal and outdoor PM_{10}† ($\mu g/m^3$) and several other variables, Amsterdam, Netherlands, 1994 ($n = 256$)

	Parameter estimate	SE†	95% CI†	Mean of the variable
Intercept ($\mu g/m^3$)	4.35	5.96	−7.76 to 16.46	
No. of cigarettes smoked in the living room	2.33**	0.70	0.94 to 3.72	0.56‡
No. of hours spent in the presence of smokers	5.70**	1.38	2.98 to 8.43	0.57§
Living along a busy road (yes/no)	22.73**	5.36	11.84 to 33.62	0.20
Time spent in a vehicle (hours)	5.42*	2.73	0.05 to 10.80	0.29
Cooking (yes/no)	4.82	3.89	−2.86 to 12.50	0.81
Cleaning activities (yes/no)	2.16	3.06	−3.87 to 8.19	0.58
Time spent outdoors (hours)	−1.19	1.33	−3.81 to 1.43	1.29
Sex (♀ = 0, ♂ = 1)	3.80	4.37	−5.08 to 12.67	0.50
Living room window opened (yes/no)	−1.60	3.61	−8.71 to 5.51	0.38
Slept with bedroom window opened (yes/no)	1.40	3.76	−6.01 to 8.80	0.61

* $p < 0.05$; ** $p < 0.01$.
† PM_{10}, particulate matter with a 50% cutoff diameter of 10 μm.; SE, standard error; CI, confidence interval.
‡ Smoking in the living room was reported 26 times.
§ Exposure to environmental tobacco smoke elsewhere was reported 64 times.

TABLE 5. Multiple regression analysis of the relation between the difference between indoor and outdoor PM_{10}† ($\mu g/m^3$) and several other variables, Amsterdam, Netherlands, 1994 ($n = 241$)

	Parameter estimate	SE†	95% CI†	Mean of the variable
Intercept	−12.48**	3.32	−19.23 to −5.74	
No. of cigarettes smoked in the living room	2.33**	0.51	1.32 to 3.34	0.59‡
Cooking, kitchen in living room (yes/no)	6.95*	3.94	−0.81 to 14.71	0.20
Cooking, kitchen elsewhere (yes/no)	0.60	3.04	−5.40 to 6.59	0.62
Cleaning activities (yes/no)	2.97	2.31	−1.59 to 7.52	0.58
Living along a busy road (yes/no)	−2.12	3.48	−9.19 to 4.95	0.17
Living room window opened (yes/no)	2.19	2.46	−2.67 to 7.04	0.39

* $p < 0.10$; ** $p < 0.001$.
† PM_{10}, particulate matter with a 50% cutoff diameter of 10 μm.; SE, standard error; CI, confidence interval.
‡ Smoking in the living room was reported 23 times.

some other characteristics associated with living along a busy road are responsible for the effect.

The time spent in a vehicle also significantly contributed to the difference between personal and outdoor concentrations. The estimated contribution was 5.4 $\mu g/m^3$ per hour spent in a vehicle. To cause such an increase in the 24-hour-averaged personal concentration, the PM_{10} concentration in the vehicle must have been about 130 $\mu g/m^3$ (24 hours × 5.4 $\mu g/m^3$ per hour) higher than the outdoor concentration. Although several studies have been conducted on the exposure of car drivers to gaseous traffic-related air pollutants (25–27), limited information is available about particle concentrations inside vehicles. Morandi et al. (28) measured the personal concentrations of respirable suspended particulates of 30 subjects for 12 hours, using a portable piezobalance-type respirable mass monitor with 5-minute integration times. The mean concentration of respirable suspended particulates inside vehicles was 35 $\mu g/m^3$, significantly higher than the mean outdoor concentrations of 22 $\mu g/m^3$, but suggesting smaller differences than the difference necessary to explain our estimated contribution of 5.4 $\mu g/m^3$ per hour. However, the results are not directly comparable because of the difference in the particle sizes measured (respirable suspended particulates vs. PM_{10}). Possibly resuspension of the coarse part of PM_{10} particles, caused by the presence of persons in the small volume of a car, is responsible for (part of) the difference.

Cooking in a kitchen with an open connection to the living room increased the indoor PM_{10} concentrations. The influence of cooking on personal exposures was lower and not significant. Cleaning activities did not have a significant effect on personal or indoor concentrations. In addition to exposure to ETS, several studies identified cooking as a second important source of particles (11). In the PTEAM study, Ozkaynak et al. (29) found that cooking added about 12 and 26 $\mu g/m^3$ to nighttime and daytime indoor PM_{10} concentrations,

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respectively. Other household activities such as vacuuming and dusting appeared to make smaller contributions to indoor particle levels. Morandi et al. (28) also found higher concentrations of respirable suspended particulates in the presence of active cooking (mean, 27 $\mu g/m^3$) than in the absence of cooking emissions (mean, 20 $\mu g/m^3$). Buckley et al. (13) reported that housecleaning and cooking were important activity variables in improving the correlation between personal and outdoor PM_{10} concentrations. Quantitative information about the contribution of these activities, however, was not provided.

Excess personal exposures compared with indoor or outdoor concentrations have been found in most personal exposure studies (11, 29), with the exception of some studies among disabled or retired persons (30) and patients with severe chronic obstructive pulmonary disease (31). Resuspension of coarse particles by personal activities and proximity to particle-generating sources have been suggested as causes of this so-called personal cloud (11). For the older adults studied in this study, the major part of the difference between personal and outdoor PM_{10} concentrations could be attributed to exposure to ETS, living along a busy road, and the time spent in a vehicle.

In conclusion, this study has shown that personal PM_{10} concentrations are reasonably well correlated with ambient PM_{10} concentrations, within subjects, over time. This finding provides support for using fixed site measurements as a measure of exposure to PM_{10} in time series studies linking the day-to-day variation in PM_{10} to the day-to-day variation in health endpoints.

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